

## ROTATION AND TRANSLATION MEASUREMENT

## CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation-in-part of U.S. Application Serial No. 09/434,100 filed  
5 Nov. 5, 1999, which is a continuation-in-part of U.S. Application Serial No. 08/812,998 filed  
March 4, 1997, now U.S. Patent No. 5,991,112 issued Nov. 23, 1999.

## TECHNICAL FIELD

10 The present invention relates generally to the field of optical measurement, and more  
particularly to accurately detecting positional characteristics of a fixed or moving measurement  
target. It is anticipated that primary applications of the present invention will be in  
manufacturing of highly precise assemblies and in industrial and laboratory processes requiring  
high precision position detection and control.

## BACKGROUND ART

15 Many present industries and fields of research are encountering a need for faster and  
more accurate position and movement determination. For example, in semiconductor fabrication  
and disk drive assembly the capacity of the ultimate end product depends highly on the accuracy  
of the measurement systems used, while the economy of the product often depends highly on the  
20 speed of the measurement systems used.

Many different measurement systems exist and are in wide use today. Of present interest  
are optical measurement systems, since they often permit non-contact measurement and have  
many other desirable characteristics. Present optical systems range from simple triangulation  
systems which use light beam reflection and geometric principles known since ancient times, to  
25 complex laser systems which use interferometric principles to achieve accuracy to within  
fractions of one light wavelength. However, particularly as modern applications become  
increasingly complex, the often conflicting goals of measurement accuracy and manufacturing  
speed remain ones where many seek further improvement.

FIG. 1 (background art) stylistically depicts a measurement system 10 for determining  
30 positional information about a movement stage 12. As FIG. 1 illustrates with linear and circular  
arrowed lines, the movement stage 12 can have its position defined with respect to numerous

coordinate systems. For example, positional information about the movement stage 12 can be with respect to each of x, y, and z linear axes, as well as with respect to each of rotational axes for pitch, yaw, and roll. The movement stage 12 thus can be viewed as having as many as six degrees of freedom. Of course, and as often is the case, movement may be limited to only some of or may not be of interest in only some of these degrees of freedom, but accurate and fast measurement is still often a daunting task.

FIG. 1 includes a first detector 14, a second detector 16, a third detector 18, a controller 20, and an external system 22. The first detector 14 can detect position relative to the x-axis, and provide positional information with respect to this to the controller 20. The second detector 16 can detect position or displacement relative to the y-axis, and provide further positional information about this to the controller 20. The third detector 18 can detect position or displacement relative to the z-axis and provide information about this to the controller 20.

Practitioners of the optical measurement arts will recall that many common detectors today are only able to detect positional change. For example, interferometers can only detect target displacement, a relative position measurement, and not initial or absolute position. Further, if displacement occurs too slow or too fast even these techniques will fail. Herein we generally discuss absolute and relative measurement techniques collectively unless particular differences are important.

Returning to FIG. 1, the controller 20 there provides the positional information it receives, perhaps after appropriate processing and format conversion, to the external system 22. The external system 22 may simply be a display unit that a human user reads, or it may be a servo feedback system precisely controlling various movements of the movement stage 12 in a complex manufacturing process. The external system 22 is thus "external" with respect to the measurement process used; it is merely a recipient of and an ultimate user of the results of the measurement system for some higher purpose.

Unfortunately, the simple position determining system of FIG. 1 can only provide positional information about three degrees of freedom for the movement stage 12. It cannot, for example, tell us anything about roll as depicted by the rotational arrowed line 24. Using detectors of the sort depicted here, adding roll detection would require adding at least a fourth detector 26 (depicted in ghost form) in parallel with the second detector 16. Doing this would thus entail the expenses of more detector hardware, increased controller capability to handle the additional

burden of this, and the attendant set-up and maintenance of the more complex position determining system which would result. If the detectors which are used are laser interferometers, as might very well be the case today in a manufacturing or laboratory scenario where high accuracy is necessary, the expense of another detector could be quite appreciable. The costs of additional set-up and maintenance would also likely be appreciable. However, and worth noting for later in this discussion, the added cost for increased controller capability might be quite negligible.

Accordingly, what is needed is a position determining system which employs relatively simple detection hardware yet provides positional information for a measurement target with respect to multiple axes.

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## DISCLOSURE OF INVENTION

Accordingly, it is an object of the present invention to provide a position determining system which provides information about a measurement target with respect to multiple axes or  
5 degrees of freedom.

Another object of the invention is to provide a position determining system which provides information on absolute or initial position, as contrasted with merely relative position based on measurement target displacement.

Another object of the invention is to provide a position determining system which  
10 concurrently provides both rotation and translation of positional information.

And, another object of the invention is to provide a position determining system which is fast in operation yet provides positional information which is highly accurate.

Briefly, one preferred embodiment of the present invention is a measuring apparatus. A light source produces light beams for at least two optical channels. In each optical channel, an  
15 interferometer is provided to receive one light beam and provide from it a reference beam and a measurement beam. A reflective target then receives and redirects the measurement beam. A beam splitter for receives the redirected measurement beam and provides from it a first and second portions. A detector for senses the first portion and produces a detector signal based on it. The interferometer further receives the second portion of the measurement beam and combines it  
20 with the reference beam to form a result beam. A receiver is senses the result beam and produces a receiver signal based on it.

An advantage of the present invention is that it provides highly desirable non-contact position determination, based on its use of optical principles. Further, due to its ability to employ lasers as a light source, the invention may be used for measurement targets ranging from small to  
25 quite large and at distances ranging from near to quite remote.

Another advantage of the invention is that it permits measurement of combinations of positional characteristics which have previously been difficult to attain with a limited component count. For example, using two parallel optical channels it can measure target translation or straightness in a perpendicular x-y plane as well as target roll in the x-y plane. The invention is  
30 thus effectively able to measure three axes or degrees of freedom with only two sensors. Still additional sensors can also be added to provide yet further capability

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Another advantage of the invention is that its speed of measurement is considerably less limited than is the case for relative type measurement systems. The invention can accurately measure position when a target is at rest, i.e., zero speed, and also when a target is moving quite slowly or decelerating toward or accelerating from rest. Thus, the present invention does not suffer from a "zero-barrier" limitation like conventional interferometer systems. The invention can also accurately measure position when a target is moving fast, i.e., has a high slew rate. In the present invention, the permissible target speed is limited merely by the sensor response times and the electronics used for signal processing, which can be quite. This is in marked contrast to conventional laser interferometer systems, which are today severely limited by the obtainable beam frequency differential.

And, another advantage of the invention is that it is economical to construct and operate, particularly in comparison with conventional systems producing similar accuracy and measurement speed such as laser interferometer based systems.

These and other objects and advantages of the present invention will become clear to those skilled in the art in view of the description of the best presently known mode of carrying out the invention and the industrial applicability of the preferred embodiment as described herein and as illustrated in the several figures of the drawings.

## BRIEF DESCRIPTION OF THE DRAWINGS

The purposes and advantages of the present invention will be apparent from the following detailed description in conjunction with the appended drawings in which:

5        FIG. 1 (background art) is a perspective view of how a conventional laser interferometer measurement system is used to determine the position of a movement stage;

FIG. 2 is an perspective view of an embodiment of the present invention in use to determine positional information about a movement stage;

10        FIG. 3 is a block diagram in top plan view particularly showing the detection section of the embodiment of FIG. 2;

FIG. 4 is a block diagram functional representation of the control section;

FIG. 5 is a graph depicting details of the preferred modulation signal provided by the control section;

15        FIG. 6 is a side elevation view of the face of the movement stage illuminated in an optimal initial set-up manner by light beams from the detection section;

FIG. 7 is a side elevation view of the face of the movement stage particularly showing movement axes, light beam centers, and a light beam separation distance for the view of FIG. 6;

FIG. 8 is a block diagram in top plan view depicting an alternate preferred embodiment of the invention;

20        FIG. 9a-e depict various side elevation views of the face of the movement stage, in which: FIG. 9a is of an optimal initial set-up or starting arrangement, FIG. 9b is of the movement stage after rightward movement, FIG. 9c is of the movement stage after upward movement, FIG. 9d is of the movement stage after diagonal rightward-upward movement, and FIG. 9e is of the movement stage after counter-clockwise roll; and

25        FIG. 10 is a perspective view depicting a sophisticated embodiment of the invention forming a multiple parameters measurement system.

FOOTNOTES

## BEST MODE FOR CARRYING OUT THE INVENTION

A preferred embodiment of the present invention is a position determining system (hereinafter "PDS"). As illustrated in the various drawings herein, and particularly in the views of FIG. 2 and 5, the inventive device is depicted by the general reference character 100. Where appropriate, reference numbers are reused in the figures.

FIG. 2 depicts a preferred embodiment of the inventive PDS 100 in a generic usage scenario for determining positional information about a typical movement stage 12, such as that of FIG. 1 (background art). Retroreflective targets 110 are mounted on the movement stage 12; a detection section 112 is provided to optically sense information about the retroreflective targets 110; and a control section 114 is provided to control the operation of the PDS 100 and to communicate with an external system 22. The movement stage 12 and the external system 22 are not formally parts of the inventive PDS 100. As discussed with respect to FIG. 1 (background art) the movement stage 12 may be a simple stage of any type which one wants to know positional information about. Typically, but not necessarily in all applications, the external system 22 will control movement of the movement stage 12 using servo feedback techniques and also display or record positional information about the movement stage 12 at various points in a manufacturing or laboratory process.

FIG. 3 is a top view particularly showing the components and functions of the detection section 112. Modulation is applied to one or more light sources 122, via a bus 120 connected to the control section 114. Details for the preferred form of modulation are discussed presently. Typically the light source 122 produces two light beams 124 (two light sources 122 are shown here). The inventor's preferred light source 122 includes a conventional laser diode.

Each light beam 124 is passed through a polarizing plate 126. This is desirable because many light sources, including laser diodes, do not produce light which is strongly polarized. The polarized light beams 124 then pass directly through respective polarized beam splitters 128, which have been suitably positioned and oriented to permit this. Each light beam 124 is next passed through a retardation plate 130 (e.g., a conventional 1/4 wave plate), where the polarization of the light beam 124 is altered. The light beams 124 then exit the detection section 112, proper, and travel onward to and are reflected back by respective retroreflective targets 110 which are mounted on the movement stage 12.

The return paths of the light beams **124** are somewhat similar to those already taken, but not completely so. After reflection by the retroreflective targets **110**, the light beams **124** re-enter the detection section **112**, and each again passes through its respective retardation plate **130**. The already once altered polarizations of the light beams **124** are accordingly further altered by this  
5 second passage. The light beams **124** then re-enter the polarized beam splitters **128**. However, due to their now altered polarizations and the orientations of the polarized beam splitters **128**, the light beams **124** are each now redirected into a respective sensor unit **132**. The sensor units **132** each detect a respective returned light beam **124** and create information which is communicated to the control section **114** via the bus **120**. The inventor's preferred sensor unit **132** includes a  
10 quad-cell photo detector.

As initially noted, two light beams **124** are typically produced. FIG. 3 thus can be viewed as depicting two optical channels **134**. The use of two such optical channels **134** particularly permits the inventive PDS **100** to measure a number of positional characteristics, as will be described presently. Embodiments having as few as one and more than two optical channels **134**  
15 are also possible.

FIG. 4 is a block diagram particularly showing the functional operation of the control section **114**. A frequency generator **140** produces a modulation signal **142** which is communicated over the bus **120** to the light sources **122** in the detection section **112**, where it is used to modulate each light beam **124** (FIG. 4 depicts only one of the optical channels **134** of the embodiment of FIG. 3).  
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FIG. 5 depicts details of the preferred modulation signal **142**. The frequency of modulation is above 30 kHz, but this is merely a matter of design choice. In applications which the inventor currently has in development, using such a frequency helps to obtain appropriate slave servo bandwidth in the high speed external system **22**. The waveform used preferably also  
25 has a linear transition **144** at zero crossing. This facilitates electronic signal processing, but also is not a necessity. A suitable shape for the modulation signal **142** thus might be the trapezoidal waveform **146** which is shown.

FIG. 6 depicts the faces of both of the sensor units **132** mounted on the movement stage **12** of FIG. 3 (or FIG. 8), being illuminated in their very centers by the light beams **124**. This is  
30 an optimal initial set-up arrangement for the PDS **100** and the movement stage **12** since it provides for ranges of movement in many directions. As shown, when using quad-cell photo



diodes for the sensor units **132**, quadrants A, B, C and D are defined for the left sensor unit **132** and quadrants E, F, G and H are defined for the right sensor unit **132**. The sensor units **132** thus each have a center point **202** where the quadrants meet and the respective light beams **124** have a center separation **148** (S), as shown. It is desirable, but not necessary (since compensation in the control section **114** can accommodate for some degree of offset), that the center points **202** of the sensor units **132** be spaced apart a distance equal to the center separation **148** of the light beams **124**. Another way of envisioning all of this is to view the light beams **124** as having central axes (not shown in FIG. 6 but easily seen in the stylistically simplified light beams **124** of FIG. 3, for example), and appreciating that in an optimum set-up scenario each such central axis intersects the center point **202** of a sensor unit **132**.

FIG. 7 shows how the movement stage **12** may have an x-axis **204** and a y-axis **206** defined with a common origin **208**. For conceptual purposes it is useful to orient the intersections **210** of the quadrants of the sensor units **132** the same and parallel with the x-axis **204** and y-axis **206**, but the underlying mathematical principles of the invention are not affected by this.

Returning now to FIG. 4, the sensor units **132** receive the light beams **124**, in the manner previously described for FIG. 3, and each produces raw signals **150** which are communicated over the bus **120** back to the control section **114**. For the quad-cell type sensor units **132** used here, each cell-quadrant produces a raw signal **150**, and thus four are created for each optical channel **134** (i.e., eight for the embodiment of FIG. 3).

The sensor units **132** are typically direct current (DC) biased, and hence the raw signals **150** each have both DC and alternating current (AC) signal elements at this early stage. Unfortunately, the DC element is subject to thermal and other types of drift, which is a particular weakness of many present detectors. The effects of such drift must be eliminated before high gain amplification is used in later signal processing. To remove the undesirable DC elements, the raw signals **150** are fed into differential amplifiers **152** which couple only the AC elements and create quadrant A-B, B-C, C-D, and D-A difference signals **154**.

Each difference signal **154** and the respective components used to further process it may collectively be viewed as an electrical channel **156**. FIG. 4 depicts only one such electrical channel **156**, but the embodiment of FIG. 2 might employ eight such channels or use multiplexing (not shown) to lower the electrical channel count. The inventive spirit of the PDS encompasses such alternates.

Once the difference signals **154** have the undesirable DC elements removed there are usually still undesirable AC elements also present. For example, room lighting may introduce such undesirable AC elements. If incandescent lighting is used in a measurement area it may introduce 60 hertz AC signal elements, and if fluorescent lighting is used it may introduce various higher frequency AC signal elements. Eliminating such undesirable AC elements is of key importance, and the manner in which the inventor does this is new to the art of optical position measurement.

A sample of each difference signal **154** is processed by a first synchronous demodulator **158** and passed through a first low pass filter **160** to obtain a coarse position signal **162**. Since the first synchronous demodulator **158** operates directly on the low gain difference signal **154**, high precision demodulation is not required here, and conventional analog switches and operational amplifiers may be used.

Another sample from each difference signal **154** is amplified with a high gain amplifier **164** to produce a highly amplified signal **166**. In the preferred embodiment, an operational amplifier configured as an inverting amplifier is used for the high gain amplifier **164**, to provide a gain of 500 and to thereby obtain heightened sensitivity in the PDS **100**. The highly amplified signal **166** is then processed by a second synchronous demodulator **168**, and is passed through a second low pass filter **170** to obtain a fine position signal **172**. The second synchronous demodulator **168** usually must be of high precision, due to the sensitive nature of the highly amplified signal **166**.

In the preferred embodiment the second synchronous demodulator **168** and the second low pass filter **170** are combined in a board level, lock-in amplifier system which serves as a high quality balanced demodulator and a 6th order high quality filter. A suitable component for this is a "Lock-in Engine" which is commercially available from Quanta Physik, Inc. of Palm Beach Gardens, Florida, USA. ("The lock-in amplifier is basically a synchronous demodulator followed by a low pass filter .... Lock-in amplification is a technique which is used to separate small, narrow band signal content from interfering noise. The lock-in amplifier acts as a detector and narrow band filter combined. Very small signals can be detected in the presence of large amounts of non-correlated noise when the frequency and phase of the desired signals are known." From AD630 Application Note by Analog Devices, Inc. of Norwood, Massachusetts. Quanta Physik's Lock-in Engine is built around the AD630 component.)

The coarse position signal **162** and the fine position signal **172** are provided to a logic unit **174**, and optionally also directly to the external system **22**. The logic unit **174** will typically include powerful microprocessor capabilities which will depend considerably on the capabilities of the external system **22** and the needs of the application in which the PDS **100** is used.

5 A communications link **176** is provided between the logic unit **174** and the external system **22**. This communications link **176** may be bi-directional, permitting the external system **22** to transmit instruction signals **178** to the logic unit **174** for when to operate the PDS **100** and obtain the coarse position signal **162** and fine position signal **172**, and also permitting the PDS **100** to transmit processed position data in a result signal **180** back to the external system **22**.

10 FIG. 8 depicts an alternate preferred embodiment of the inventive PDS **100**. Here, the sensor units **132** are instead directly mounted on the movement stage **12**, in place of the retroreflective targets **110** of FIG. 2, and a targeting section **190** optically "targets" the remote sensor units **132**. The same control section **114** as previously described can also control the operation of the PDS **100** and communicate with the external system **22** in this embodiment.

15 The targeting section **190** used here may be much simpler optically than the detection section **112** of FIG. 2 and 3. A light source **122** again is present and used to provide light beams **124** which are modulated with the modulation signal **142** from the control section **114**. A major change, however, is that no polarization related components are needed. The sensor units **132** which are mounted directly on the movement stage **12** are illuminated directly by the light beams **124**, without using reflection and any intervening optical components between them and the light  
20 sources **122**. The sensor units **132** may work essentially the same as previously discussed for FIG. 2-4, producing the same raw signals **150**.

While optically much simpler, this alternate embodiment may sometimes be more complex mechanically and electronically, and accordingly more troublesome to employ. For  
25 example, if the separation between the light sources **122** and the sensor units **132** is great, the electrical cable used to carry the raw signals **150** may be easily abused and damaged. Also, the raw signals **150** may be unduly attenuated or corrupted by electrical noise when traveling long distances.

FIG. 9a-e depict side elevation views of the face of the movement stage **12** of FIG. 8.  
30 Further, as those skilled in the optical arts will appreciate, the conceptual principle in the following discussion applies to the faces of the sensor units **132** in the embodiment of FIG. 2-3

as well. The faces of the sensor units **132** are depicted here as having quadrants A-D and E-H illuminated by the light beams **124**.

FIG. 9a is essentially the same as FIG. 7. It shows an optimal initial placement of the movement stage **12** relative to the detection section **112** or the targeting section **190**. The faces of both sensor units **132** are illuminated in their very centers by the light beams **124**. Quadrants A, B, C and D on the left sensor unit **132** and quadrants E, F, G and H on the right sensor unit **132** are all receiving equal illumination, and the raw signals **150** going to the control section **114** will indicate this. The respective light beams **124** have a center separation **148 (S)**, as shown.

FIG. 9b shows the movement stage **12** displaced laterally to the left, i.e. horizontally, from where it was in FIG. 9a. The direction of movement is thus perpendicular to the propagation direction of the light beams **124**. The illumination on the quadrants here has changed, and the raw signals **150** going to the control section **114** will now indicate this. Suitable processing in the control section **114** will therefore be able to determine if and to what extent such movement has occurred. This permits the PDS **100** to perform horizontal straightness measurement.

FIG. 9c shows the movement stage **12** displaced laterally upward, i.e. vertically, from where it was in FIG. 9a. The direction of movement is again perpendicular, but differently so, with respect to the light beams **124**. The illumination on the quadrants has also changed here, as the raw signals **150** will again indicate. Suitable processing in the control section **114** is also able to determine if and to what extent this movement has occurred. This permits the PDS **100** to perform vertical straightness measurement.

FIG. 9d is a more complex case. It shows the movement stage **12** displaced diagonally upward and to the left, i.e. both horizontally and vertically, from where it was in FIG. 9a. However, this is also well handled by the inventive PDS **100**.

FIG. 9e is a still more complex case. It shows the movement stage **12** rotated about an axis **182** (which is perpendicular to the plane of the figure and therefore depicted accordingly). In discussing FIG. 1 (background art), this type of tilt or rotational movement was identified as "roll." The PDS **100** can perform roll measurement by using appropriate processing in the control section **114** of the raw signals **150** which occur here.

The underlying principles of how the inventive PDS **100** can perform the above and other forms of translation and roll measurement are as follows. When the light beams **124** illuminate

the sensor units **132** they produce a current or voltage (depending on the type of sensor used) which is proportional to the strength of the light present. As was discussed above, the raw signals **150** are processed to eliminate undesirable elements not attributable to the light beams **124**, e.g., drift, interference from room lighting, etc.

In the preferred embodiment, the photo detector components used in the sensor units **132** each produces a current (I) for each quadrant which is proportional to the illumination received. Thus, the illumination from the left light beam **124** on the left sensor unit **132** is defined by the equation  $I_l = I_A + I_B + I_C + I_D$ . Similarly, the illumination from the right light beam **124** on the right sensor unit **132** is defined by the equation  $I_r = I_E + I_F + I_G + I_H$ .

The movement of the movement stage **12** depicted in FIG. 9b and 9c, i.e., strictly horizontal or vertical translation, may be found using the simple equations:

$$\Delta X = I_A - I_B = I_D - I_C = I_E - I_F = I_H - I_G;$$

$$\Delta Y = I_A - I_D = I_B - I_C = I_E - I_H = I_F - I_G.$$

From these it can be seen that if one is only concerned about a strictly horizontal or a strictly vertical translation, one can even dispense with using quad-cell components and simply use appropriately oriented bi-cells in the sensor units **132**.

For horizontal and vertical translation in combination, such as the situation depicted in FIG. 9d, the equations above will not work. For strictly horizontal and vertical translation together one may instead use:

$$\Delta X = (I_A + I_D) - (I_B + I_C) = (I_E + I_H) - (I_F + I_G);$$

$$\Delta Y = (I_A + I_B) - (I_C + I_D) = (I_E + I_F) - (I_G + I_H).$$

However, even these equations are not accurate if roll occurs. For ignoring roll and detecting just the horizontal and vertical translations one may use:

$$\Delta X = \text{the lesser of either } (I_A + I_D) - (I_B + I_C) \text{ or } (I_E + I_H) - (I_F + I_G);$$

$$\Delta Y = \text{the lesser of either } (I_A + I_B) - (I_C + I_D) \text{ or } (I_E + I_F) - (I_G + I_H).$$

And for determining the amount of roll (lets call this " $\theta$ ") of the movement stage **12** one may use the equation (recalling that S = the center separation **148** of the light beams **124**):

$$\Delta \theta = (((I_A + I_D) - (I_B + I_C)) - ((I_E + I_H) - (I_F + I_G))) / S.$$

Returning now primarily to FIG. 3, several changes can be made in the embodiment depicted there without departing from the spirit of the present invention. For example, the

multiple light sources **122** and polarizing plates **126** might be replaced with single instances of each, and beam splitting and bending instead used to produce the desired number of light beams **124**. The inventor prefers the depicted version because laser diodes and polarizing plates are relatively inexpensive and easy to work with. In contrast, beam splitters and benders having the requisite quality, such as partially reflective cubes and mirrors, are expensive and add to optical component alignment difficulties.

Another example would be to exchange the positions of the light sources **122** and polarizing plates **126** with those of the sensor units **132**, and to suitably orient the polarized beam splitters **128** for working with this arrangement instead. Under this variation, the light beams **124** would initially be reflected by the polarized beam splitters **128**, and then later pass directly through them when returning from the retroreflective targets **110**.

Returning to FIG. 2-3 and FIG. 8, the embodiment of FIG. 2-3 is particularly suitable for movement stages which are distant from the detection section **112**, or which move at high enough speeds that routing the bus **120** to it is undesirable. In contrast, the embodiment of FIG. 8 is simpler and cheaper. But, yet other embodiments are also possible, and are encompassed within the spirit of the inventive PDS **100**. For example, a hybrid approach would be to angularly reflect the light beams off of reflectors mounted on the movement stage and onto sensor units mounted elsewhere off of the movement stage. This would provide the optical economy of the FIG. 8 embodiment and the tether-less cable advantage of the FIG. 2-3 embodiment, but at the expense of aligning and maintaining the angular light beam reflection paths.

FIG. 10 is a perspective view depicting a more sophisticated embodiment of the inventive PDS **100**, one which the inventor terms a "multiple parameters measurement system" (MPMS **300**). The MPMS **300** includes a single laser light source **302** to provide a light beam **304**, that is split by a splitter **306** into two parts, one of which is then directed parallel with the other by a beam bender **308**. This permits the one light source **302** to serve two optical channels. Each channel includes a linear interferometer **310**, a beam splitter **312**, retroreflector **314** (mounted on a measurement target, not shown), a detector **316**, and a receiver **318**. Polarization may or may not be used, in the manner already described for the embodiment in FIG. 3. The detectors **316** are "position sensitive detectors," and may be photodiode devices such as those described for the sensor units **132** (FIG. 3 and 8)(e.g., bi-cell or quad-cell units, diode arrays etc.). In contrast, while photodiode devices may also be used in the receivers **318** the function there is to detect a

beat frequency rather than detection. Accordingly, these preferably are precision single cell units.

Operationally, in each channel, the light beam 304 enters the linear interferometer 310, where it is split into a reference beam and a measurement beam 320. The measurement beam 320 then passes through the beam splitter 312 and travels to and is reflected by the retroreflector 314 back to the beam splitter 312. This time however, the measurement beam 320 is split at the beam splitter 312 into a first beam portion which travels to the detector 316 and a second beam portion which enters the linear interferometer 310. In the linear interferometer 310 this second beam portion and the reference beam combine, interference occurs in the characteristic manner when waves combine, and the resulting beam travels on to the receiver 318 as shown.

When the retroreflector 314 undergoes lateral movement (due to rotational or translational change) the illumination of the first beam portion of the measurement beam 320 on the detectors 316 changes, and this is measurable with the respective detector 316.

When the retroreflector 314 undergoes displacing movement (due to linear displacement or yaw) a Doppler shift occurs which is proportional to the speed of this movement. The frequency of the reference beam, however, has remained constant while the frequency of the second beam, portion of the measurement beam 320 has changed. The interference accordingly changes, and the receiver 318 senses this change. With suitable frequency counting and accumulation in a control section (not shown here; see e.g., FIG. 2) the longitudinal displacement of the retroreflector 314 can thus be determined.

Of course, this occurs in both optical channels concurrently. Therefore, linear displacement can be calculated as the longitudinal displacement of one retroreflector 314 plus the longitudinal displacement of the other retroreflector 314, divided by two. Yaw can be calculated as the longitudinal displacement of one retroreflector 314 minus the longitudinal displacement of the other retroreflector 314, divided by two. Horizontal straightness movement can be calculated as the horizontal position reading of one detector 316 plus the horizontal position reading of the other detector 316, divided by two. Vertical straightness movement can be calculated as the vertical position reading of one detector 316 plus the vertical position reading of the other detector 316, divided by two. Roll can be calculated as the arctangent of the difference in the vertical position readings divided by the difference in the horizontal position readings.

In sum, the MPMS 300 can measure movement of an object with five degrees of

freedom. Only measuring pitch proves difficult, but in straightforward manner one or more optical channels can be added and it can be measured as well.

The MPMS 300 can, optionally, use modulation of the light beam 304 and phase sensitive detection, if accuracy necessitates that. However, in many cases that can be dispensed with, since performing 5-degree measurement with a single "station" comprising one MPMS 300 is useful in many measurement scenarios in its own right.

In addition to the above mentioned examples, various other modifications and alterations of the inventive PDS 100 may be made without departing from the invention. Accordingly, the above disclosure is not to be considered as limiting and the appended claims are to be interpreted as encompassing the true spirit and the entire scope of the invention.

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FOOTNOTES



## INDUSTRIAL APPLICABILITY

The present position determining system ("PDS 100") and the multiple parameters measurement system (MPMS 300) are well suited for application in detecting positional characteristics of fixed and moving measurement targets. In many industrial processes measurement stages 12 are suitable as such measurement targets, and thus these industrial process may benefit by use of the inventive PDS 100 or MPMS 300. Example industries where particular present need exists include semiconductor device fabrication and disk storage unit assembly. The invention provides measurement accuracy and speed which are desired in these industries, as well as many others.

The PDS 100 and MPMS 300 may also be highly desirable for some types of measurement due to the non-contact nature of its optical principles. Use of the invention can thus avoid undesirable interference with an underlying manufacturing process. Suitable embodiments of the PDS 100 and MPMS 300 may also overcome the range limitations of some common electrical measurement systems. Measurement systems using transducers such as LVDT and capacitive sensors have notoriously short measurement ranges, and considerable loss of reliability as the extremes of their ranges are approached. Whereas such electrical systems are typically useful only at ranges of less than one meter, optical systems, including the PDS 100, may be used at ranges up to many kilometers.

The PDS 100 and MPMS 300 are also economical. It is relatively inexpensive to construct and it is often cheaper to operate than many existing measurement systems. This is particularly notable in contrast to particular present measurement systems used in roles which the inventive PDS 100 and MPMS 300 may now fill. For example, laser interferometer systems are notoriously expensive, and the unreliability of electrical systems, alluded to above, can be quite uneconomical if manufacturing tool breakage or material scrapage occurs as a result.

As has already been described here, the PDS 100 and MPMS 300 may be constructed of relatively common and available electro-optical components such as laser diodes and photo diodes; optical components such as polarizers, beamsplitters, quarter-wave plates, and retroreflectors; and electronic components such as amplifiers, filters, and microprocessors. In view of these and other characteristics, successful and rapid construction of various embodiments of the inventive PDS 100 and MPMS 300 should be well within the capabilities of

skilled practitioners of the relevant arts once the principles taught herein are appreciated.

For the above and other reasons, it is expected that the PDS 100 and MPMS 300 of the present invention will have widespread industrial applicability and it is expected that the commercial utility of the present invention will be extensive and long lasting.

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## ROTATION AND TRANSLATION MEASUREMENT

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Atty. ref.: 60154.302001

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10	measurement system	160	first low pass filter
12	measurement stage	162	coarse position signal
14	first detector	164	high gain amplifier
16	second detector	166	highly amplified signal
18	third detector	168	second synchronous demodulator
20	controller	170	second low pass filter
22	external system	172	fine position signal
24	rotational arrowed line	174	logic unit
26	fourth detector	176	communications link
		178	instruction signals
100	PDS	180	result signal
110	retroreflective targets	182	axis
112	detection section	190	targeting section
114	control section		
120	bus	202	center point
122	light source	204	x-axis
124	light beam	206	y-axis
126	polarizing plate	208	origin
128	beam splitters	210	intersections
130	retardation plate		
132	sensor unit	300	MPMS
134	optical channel	302	light source
140	frequency generator	304	light beam
142	modulation signal	306	splitter
144	linear transition	308	beam bender
146	trapezoidal waveform	310	interferometer
148	center separation	312	beam splitter
150	raw signal	314	retroreflector
152	differential amplifiers	316	detector
154	difference signal	318	receiver
156	electrical channel	320	measurement beam
158	first synchronous demodulator		

FOOTNOTES: 11001